



Accelerated Testing and Preventive Maintenance in Acquisition, Maintenance and Operation of Vehicle Systems using Time-Dependent Reliability / Durability Principles

Amandeep Singh¹, Igor Baseski^{1,2}

¹U.S. Army, RDECOM TARDEC;

²Ph.D. Student, Oakland University

Zissimos P. Mourelatos, Jing Li

Mechanical Engineering Department

Oakland University

Rochester, MI 48309, USA

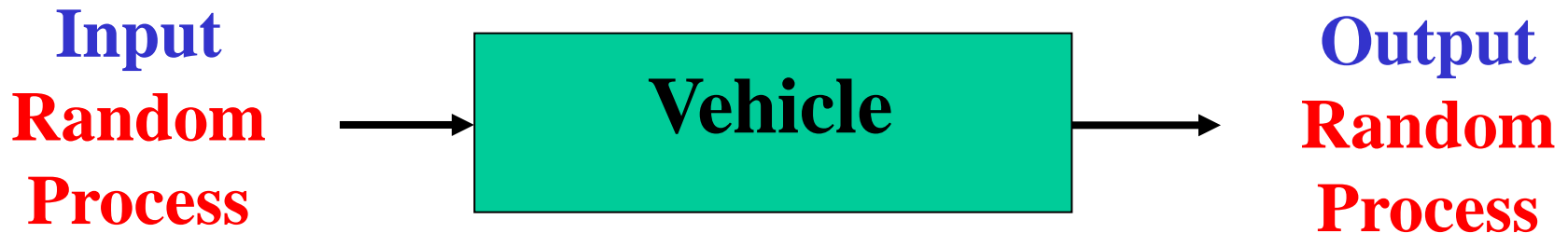
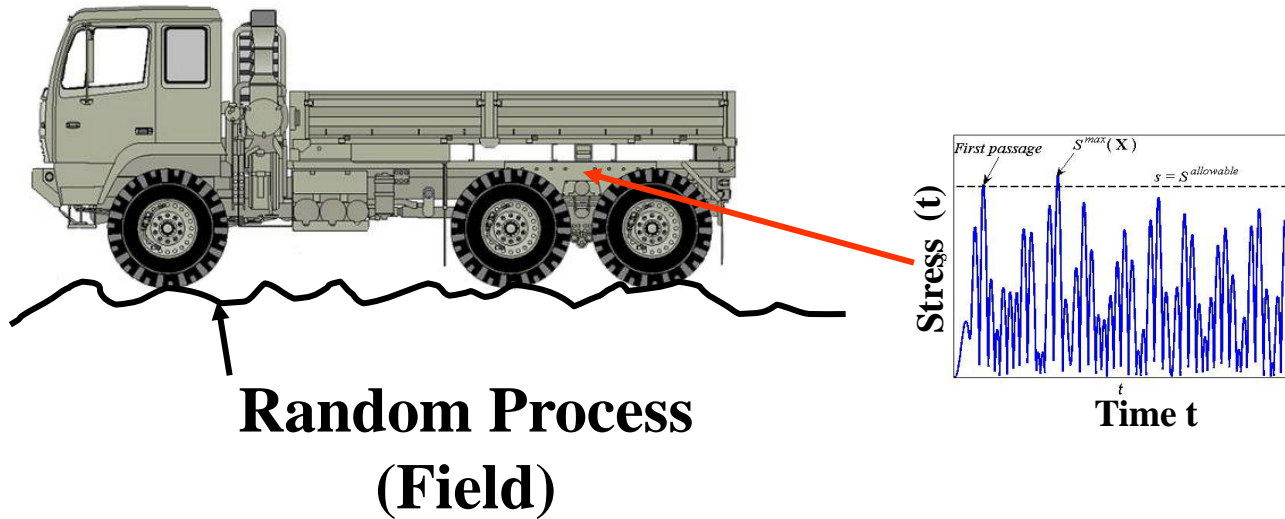
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Army Needs in Reliability, Maintenance and Logistics



- Reduce operations and **maintenance** costs
- Increase effectiveness of **fleet logistics**
- Control **lifecycle cost** and also use it in design and procurement
- Improve **availability**; **schedule maintenance**
- Use both analytical and experimental / field data to estimate reliability



Random Process leads to Time-Dependent Reliability

Develop methodologies to obtain a preventive maintenance schedule and to assess and improve the reliability / durability of vehicle systems using

- Experimental (field) data
- “Expert” opinion

Previously and currently at TARDEC

- Predictive tools (physics-of-failure data)

Current research



Part 1:

**Optimal preventive maintenance schedule
using time-dependent reliability and lifecycle cost**

Part 2:

**Accelerated testing method based on
importance sampling using few tests which run for
only a short time**



Part 1: Optimal Preventive Maintenance Schedule



What is Reliability?

Cumulative Probability of Failure

Reliability at time t is the probability that the system **has not failed before time t .**

$$F_T^c(t_L) = P(\exists t \in [0, t_L], \text{ such that } g(\mathbf{X}(t), t) \leq 0)$$

Cumulative
Prob. of Failure

$$F_T^i(t_L) = P(g(\mathbf{X}(t_L), t_L) \leq 0)$$

Instantaneous Prob. of Failure

Calculation Methods for $F_T^c(t)$

- Maximum Response Method
- Niching GA & Lazy Learning Local Metamodeling
- MCS / Importance sampling

Analytical

$$F_T^c(t) = 1 - \exp\left[-\int_0^t \lambda(t) dt\right]$$

Simulation-based

Lifecycle Cost = Production Cost

+ Inspection Cost

+ Expected Variable Cost

Quality

Time-Dependent System Reliability

$$C_L(\mathbf{d}, \mathbf{X}, t_f, r) = C_P(\mathbf{d}, \mathbf{X}) + C_I(\mathbf{d}, \mathbf{X}, t_0) + C_V^E(\mathbf{d}, \mathbf{X}, t_f, r)$$

Lifecycle Cost Production Cost Inspection Cost Expected Variable Cost

$$C_V^E(\mathbf{d}, \mathbf{X}, t_f, r) = \int_0^{t_f} c_F(t) e^{-rt} f_T^c(t) dt$$

Final time t_f Interest rate r
 Cost of failure at time t $c_F(t)$ PDF of time to failure time $f_T^c(t)$

$$F_T^c(t_L) = P(\exists t \in [0, t_L], \text{ such that } g(\mathbf{X}(t), t) \leq 0)$$

Estimation of Time for Preventive Maintenance

$$\max_{\mathbf{d}, \mu_{\mathbf{X}}, \sigma_{\mathbf{X}}, t_M} t_M$$

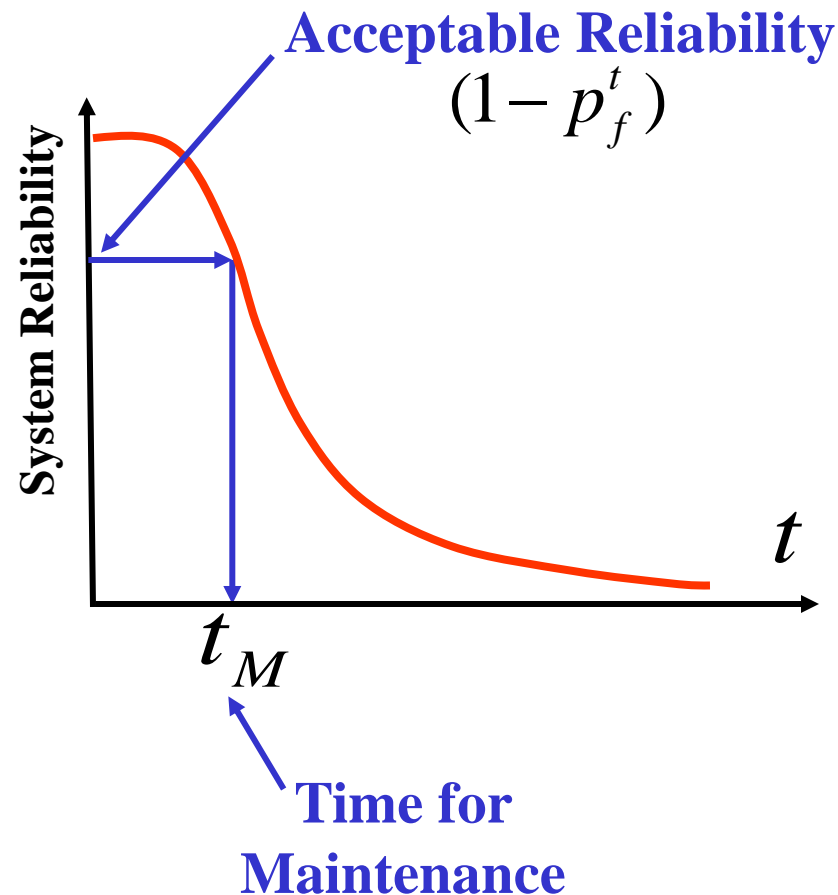
$$\text{s. t. } C_L(\mathbf{d}, \mu_{\mathbf{X}}, \sigma_{\mathbf{X}}, t_M, r) \leq C_L^t$$

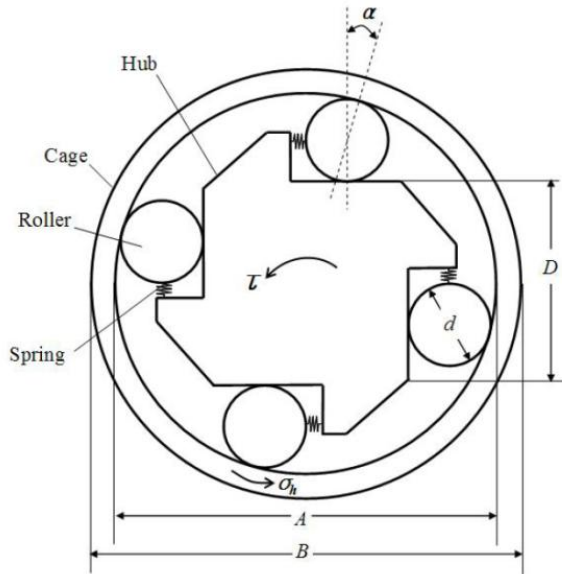
$$F_T^c(\mathbf{d}, \mathbf{X}, t_M) \leq 1 - R^t(t_M)$$

$$\mathbf{d}_L \leq \mathbf{d} \leq \mathbf{d}_U$$

$$\mu_{\mathbf{X}_L} \leq \mu_{\mathbf{X}} \leq \mu_{\mathbf{X}_U}$$

$$\sigma_{\mathbf{X}_L} \leq \sigma_{\mathbf{X}} \leq \sigma_{\mathbf{X}_U}$$





Constraints:

→ **Contact angle** $\alpha = 0.11 \pm 0.06$ rad

→ **Torque** $\tau \geq 3000$ Nm

→ **Hoop stress** $\sigma_h \leq 400$ MPa

Random Variables: D, d, A

Due to degradation:

$$D \rightarrow D(1 - kt)$$

$$d \rightarrow d(1 - kt)$$

$$A \rightarrow A(1 + kt)$$

with: $k = 2.5E-04$ mm/year

$$g_1(D, d, A) = 0.05 - \cos^{-1} \left(\frac{D - d}{A - d} \right) \leq 0$$

$$g_2(D, d, A) = \cos^{-1} \left(\frac{D - d}{A - d} \right) - 0.17 \leq 0$$

$$g_3(D, d, A) = 3000 - NL \left(\frac{\sigma_c}{c_1} \right)^2 \frac{D^2 d}{4(D + d)} \sqrt{1 - S^2} \leq 0$$

$$g_4(D, d, A) = \frac{N}{2\pi} \left(\frac{\sigma_c}{c_1} \right)^2 \left(\frac{Dd}{(D + d)} \right) \frac{S}{A} \left(\frac{B^2 + A^2}{B^2 - A^2} \right) - 400E06 \leq 0$$

$$C_L = C_P + C_I + C_V^E$$

where:

$$C_P = \left(3.5 + \frac{0.75}{3\sigma_D} \right) + \left(3.0 + \frac{0.65}{3\sigma_d} \right) + \left(0.5 + \frac{0.88}{3\sigma_A} \right)$$

$$C_I = 20F_T^i(\mathbf{X}, t_0)$$

Scrap cost/unit

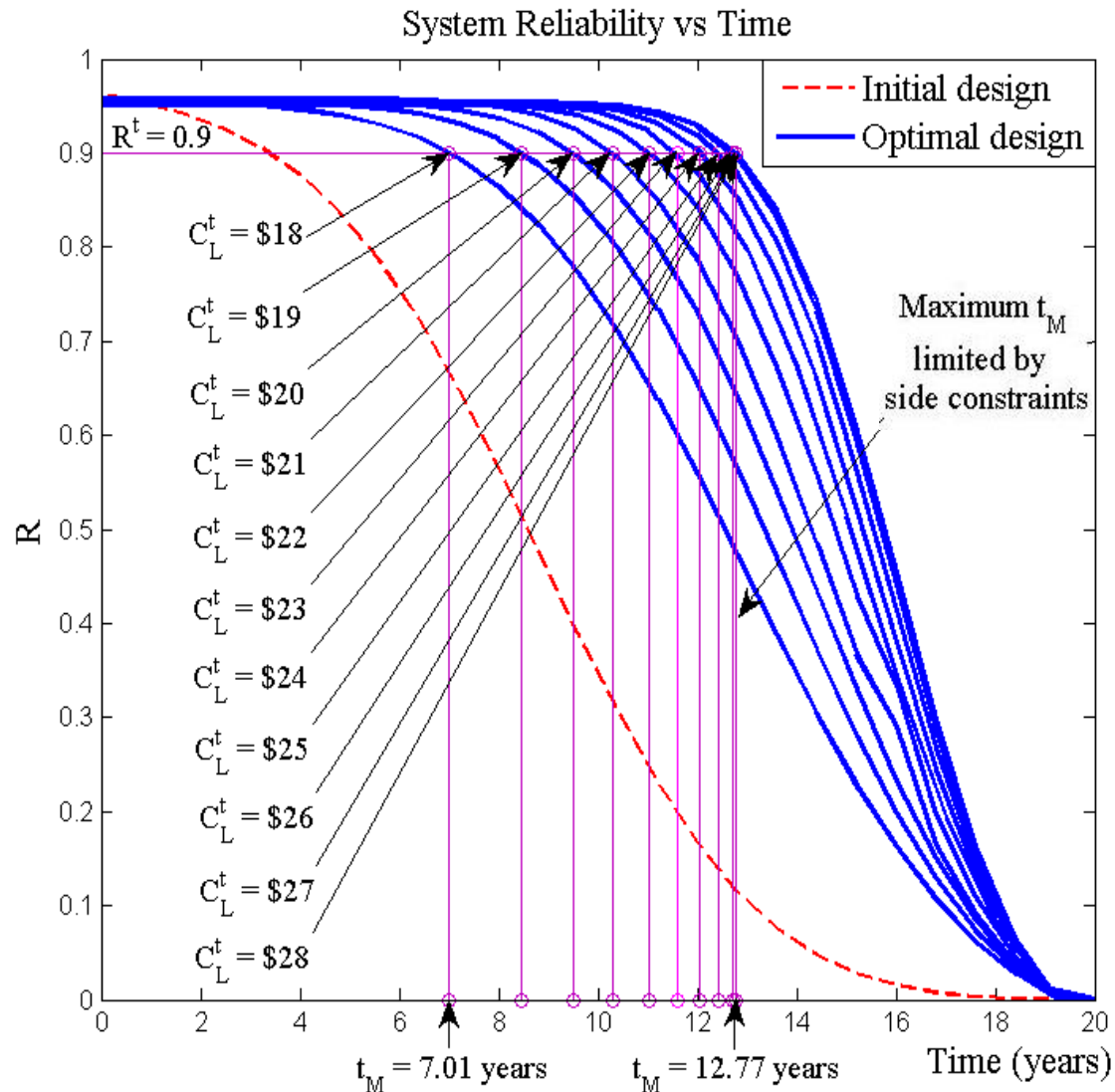
$$C_V^E = \int_0^{t_f} 20e^{-rt} f_T^c(t) dt$$

Failure cost/unit (warranty cost)

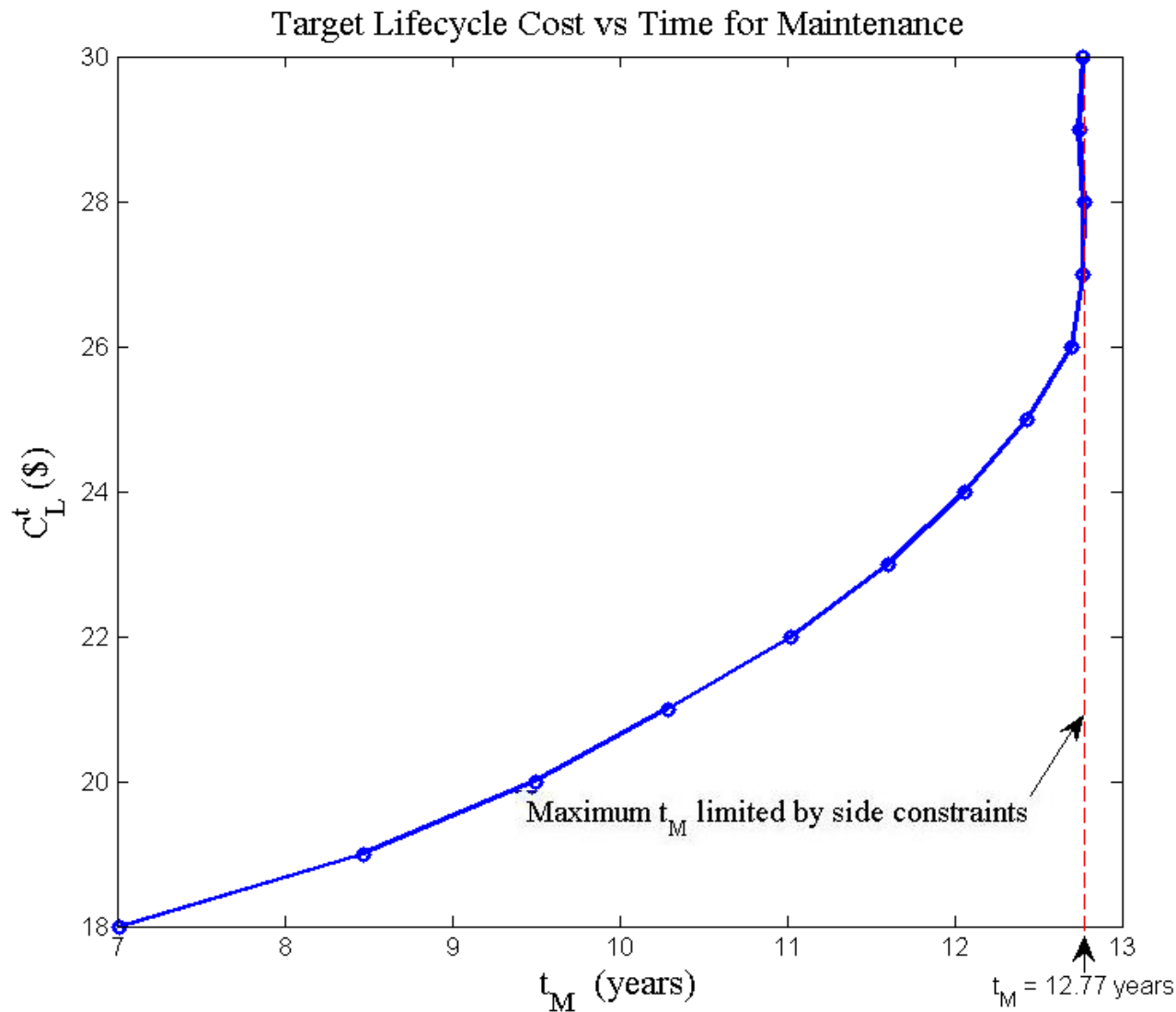
$$t_f = 10 \text{ years}$$

$$r = 3\%$$

Roller Clutch: Reliability vs Time-to-Maintenance



Roller Clutch: Pareto Optimality between Time-to-Maintenance and Cost





Roller Clutch: Pareto Optimality between Time-to-Maintenance and Cost



Design Variables:

$$\mu_{\mathbf{X}} = \{\mu_D, \mu_d, \mu_A\} \quad \sigma_{\mathbf{X}} = \{\sigma_D, \sigma_d, \sigma_A\}$$

Side Constraints:

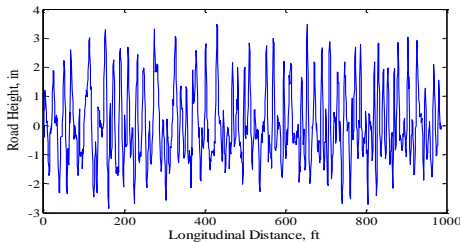
$$55.0973 \leq \mu_D \leq 55.4973 \quad 22.66 \leq \mu_D \leq 23.06 \quad 101.49 \leq \mu_A \leq 101.89$$

$$0.04 \leq \sigma_D \leq 0.08 \quad 0.03 \leq \sigma_d \leq 0.1 \quad 0.07 \leq \sigma_A \leq 0.113$$

c_L^t	18	19	20	21	22	23	24	25	26	27	28
μ_D	55.4946	55.4973	55.4973	55.3822	55.4973	55.4973	55.4973	55.4973	55.4973	55.4973	55.4973
μ_d	22.7562	22.7735	22.7867	22.8535	22.8071	22.8146	22.8208	22.8259	22.8296	22.8315	22.8316
μ_A	101.49	101.49	101.49	101.49	101.49	101.49	101.49	101.49	101.49	101.49	101.49
σ_D	0.08	0.08	0.0771	0.0693	0.0661	0.0593	0.054	0.0496	0.0423	0.04	0.04
σ_d	0.0639	0.0543	0.0481	0.0449	0.0407	0.0368	0.0334	0.0306	0.03	0.03	0.03
σ_A	0.1107	0.0946	0.084	0.0763	0.0701	0.07	0.07	0.07	0.07	0.07	0.07

Part 2: Accelerated Testing using Importance Sampling

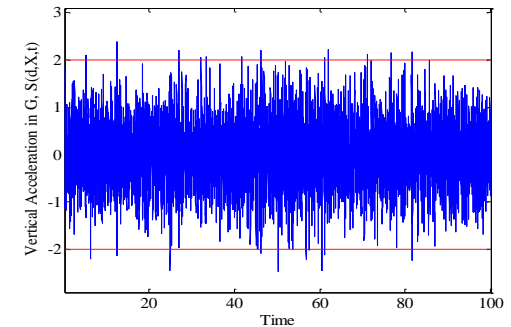
Random Variables



Terrain



Vertical Accel. (G)

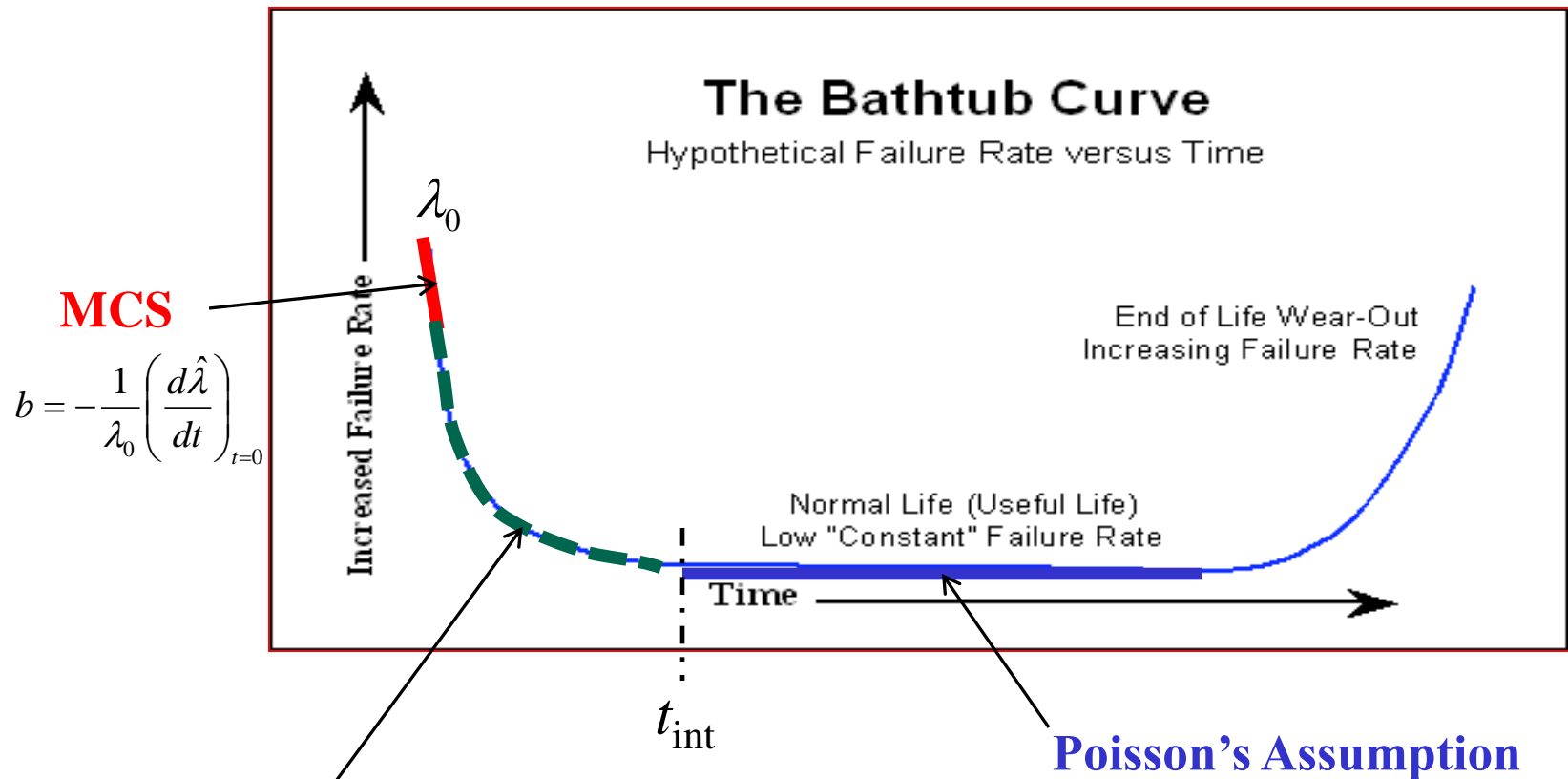


Vehicle speed : 20 mph; Mission distance : 100 miles

Simulation can be practically performed for a short-duration time

A novel MC-based method to calculate the time-dependent reliability (cumulative probability of failure) based on :

- **short-duration data and an exponential extrapolation using MCS or Importance Sampling (Infant Mortality)**
- **Poisson's assumption (Useful Life)**



**Exponential
Extrapolation**

$$\hat{\lambda}(t) \approx \lambda_0 e^{-bt}$$

$$F_T^c(t) = \begin{cases} 1 - e^{-\int_0^t \hat{\lambda}(t) dt} & , t \in [0, t_{\text{int}}] \\ 1 - (1 - F_T^c(t_{\text{int}})) e^{-v_m(t-t_{\text{int}})} & , t \in [t_{\text{int}}, t_f] \end{cases}$$

$$F_T^c(t_{\min}, t) = 1 - (1 - F^i(t_{\min}))e^{-m_1}$$

where :

$$m_1 = E[N^+(t_{\min}, t)] = \int_{t_{\min}}^t \nu^+(t) dt = \nu_m(t - t_{\min})$$

Number of out-crossings

$$\nu^+(t) = \lim_{\Delta\tau \rightarrow 0, \Delta\tau > 0} \frac{P[g(\mathbf{d}, \mathbf{X}, t) > 0 \cap g(\mathbf{d}, \mathbf{X}, t + \Delta\tau) \leq 0]}{\Delta\tau}$$

Out-crossing rate

Constant design parameters:

$$m_s = 1000 \text{ kg}$$

$$m_u = 100 \text{ kg}$$

Vehicle speed = 20 mph

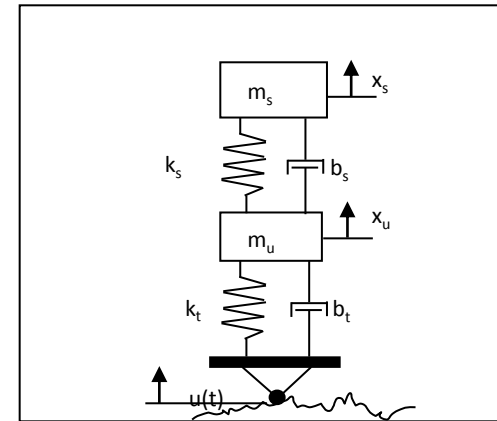
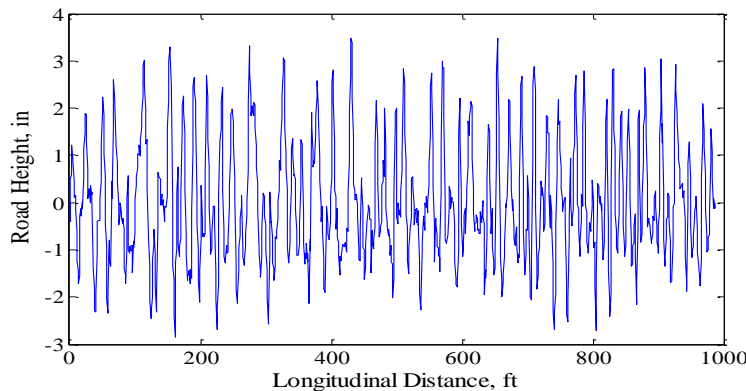


Random Input variables

Damping, $b_s \sim N(7000, 1400^2)$

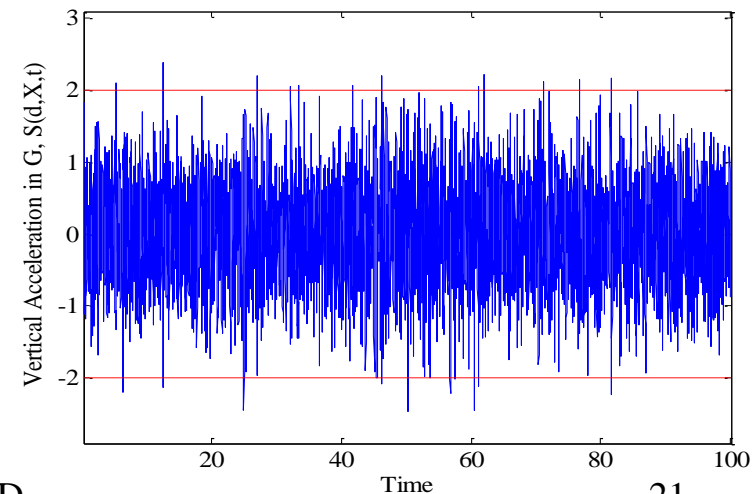
Stiffness, $k_s \sim N(40 \times 10^3, (4 \times 10^3)^2)$

Random Input Process: Experimental Stochastic Terrain from Yuma Proving Grounds.



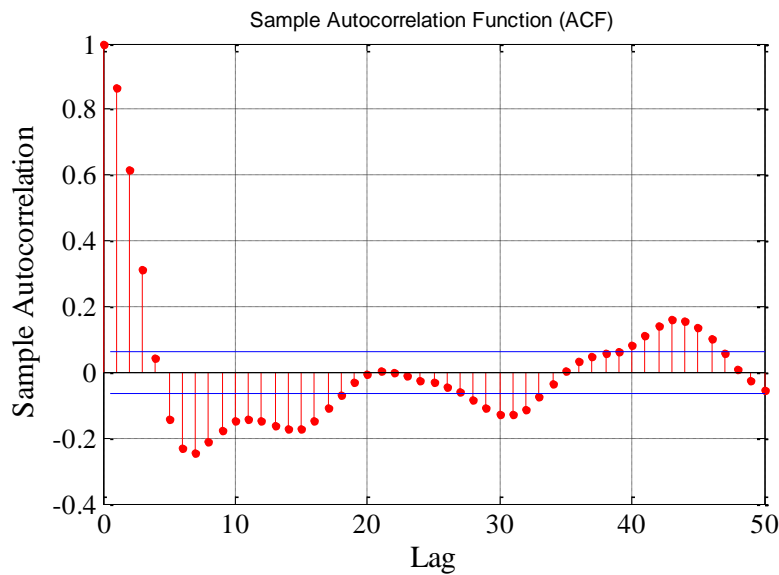
Random Output Process
(Vertical Acceleration, G')

Threshold = 2G

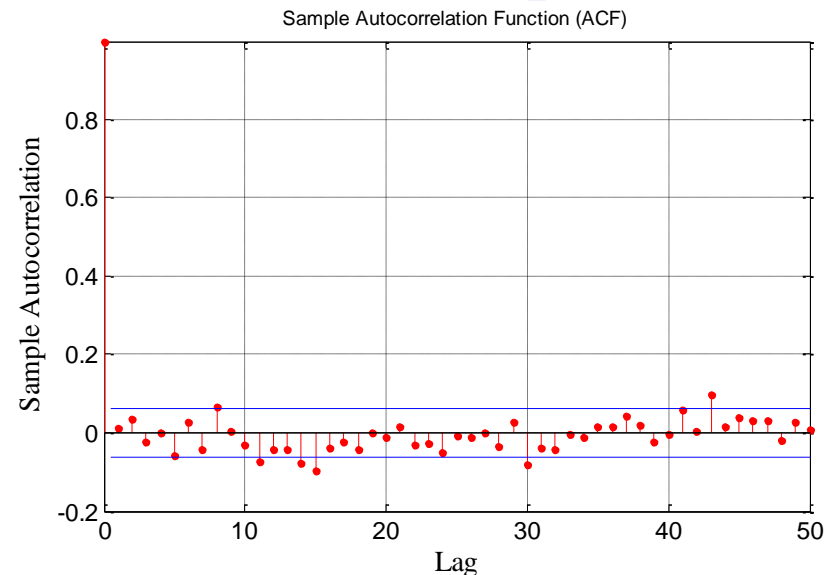


AR(3) model was identified based on:

Autocorrelation Function



Autocorrelation of Residual process

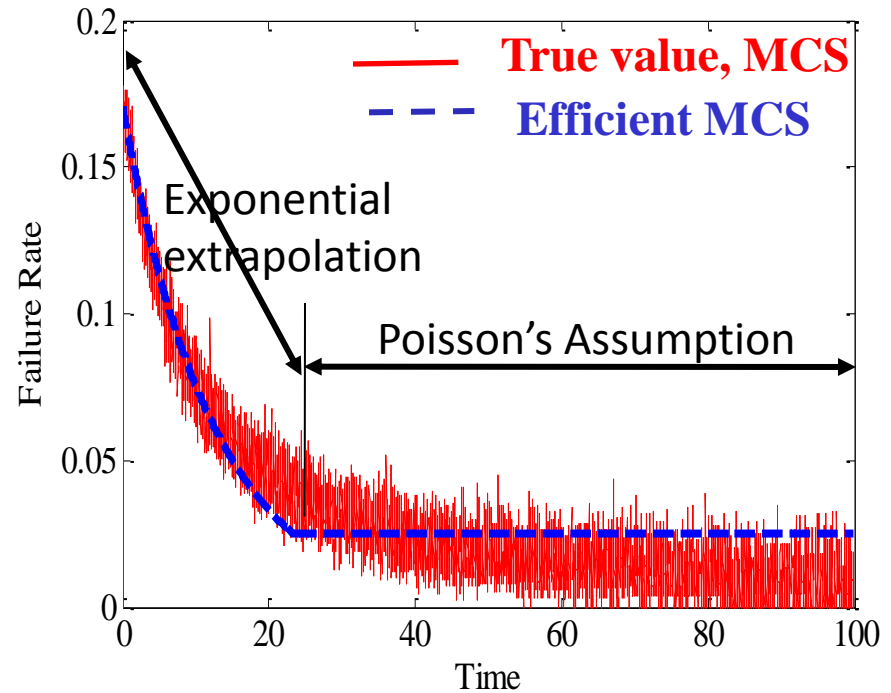
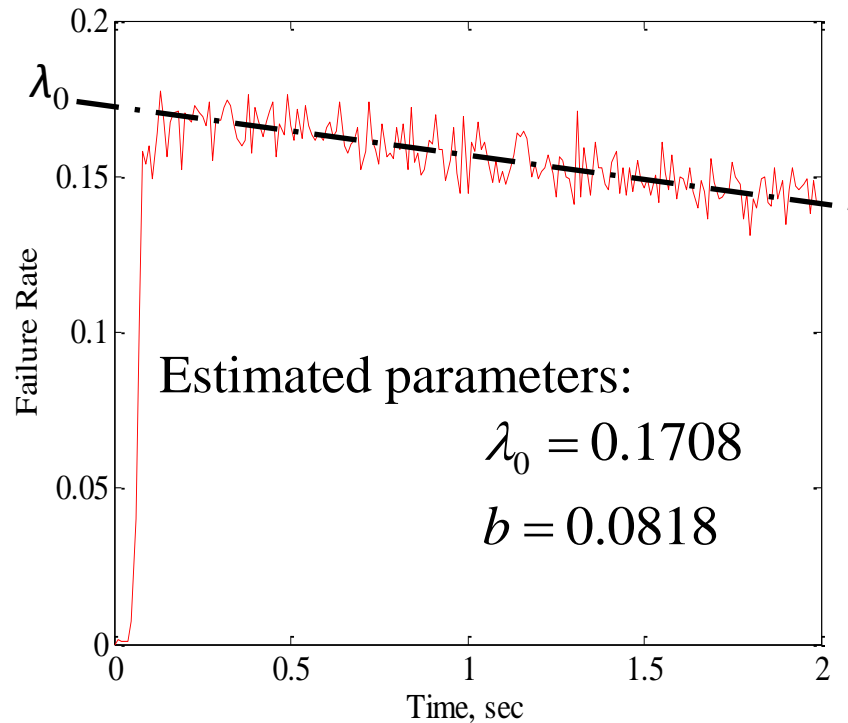


$$u_i = 1.2456 u_{i-1} - 0.2976 u_{i-2} - 0.1954 u_{i-3} + \varepsilon_i(0, 0.5132^2)$$

Statistical tests were performed to verify the model

Quarter-Car Model: Results

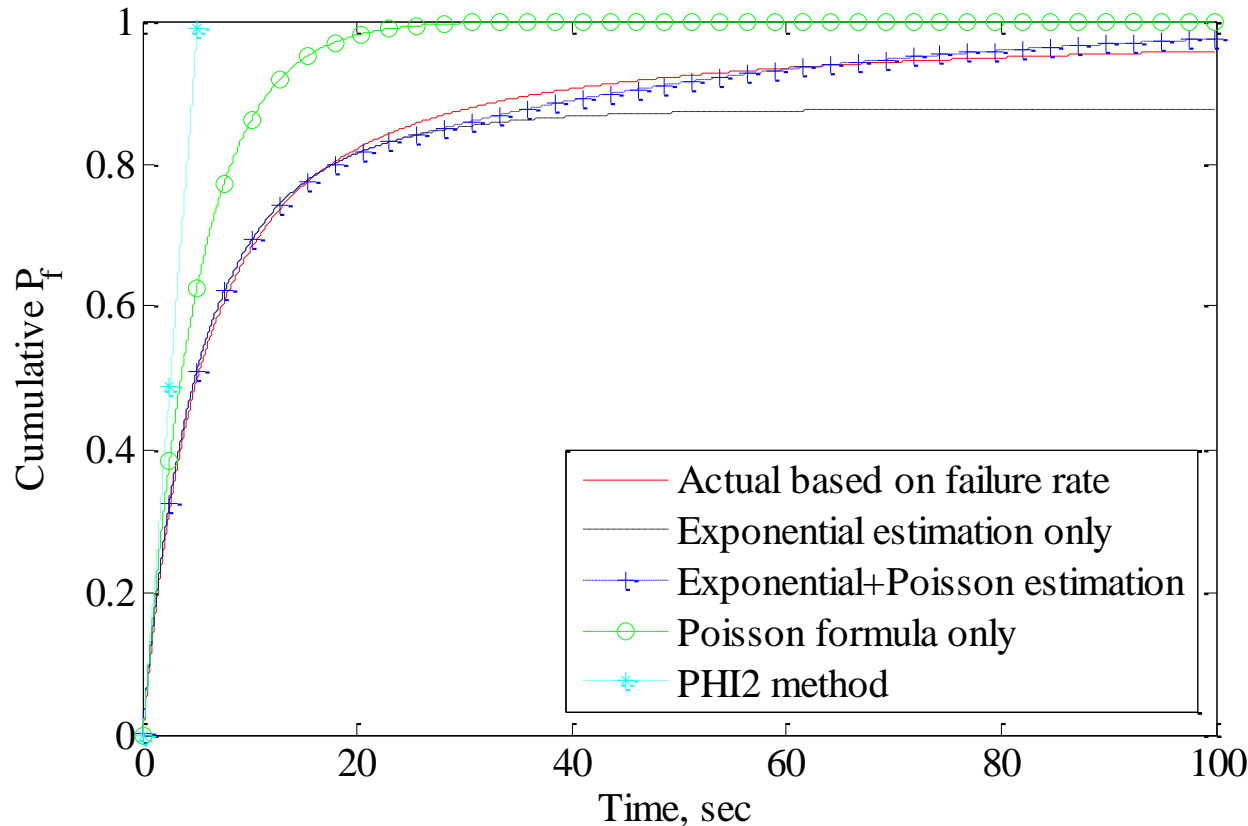
(Failure Rate Estimation for Threshold = 2G)



Estimation requires **short duration** MCS

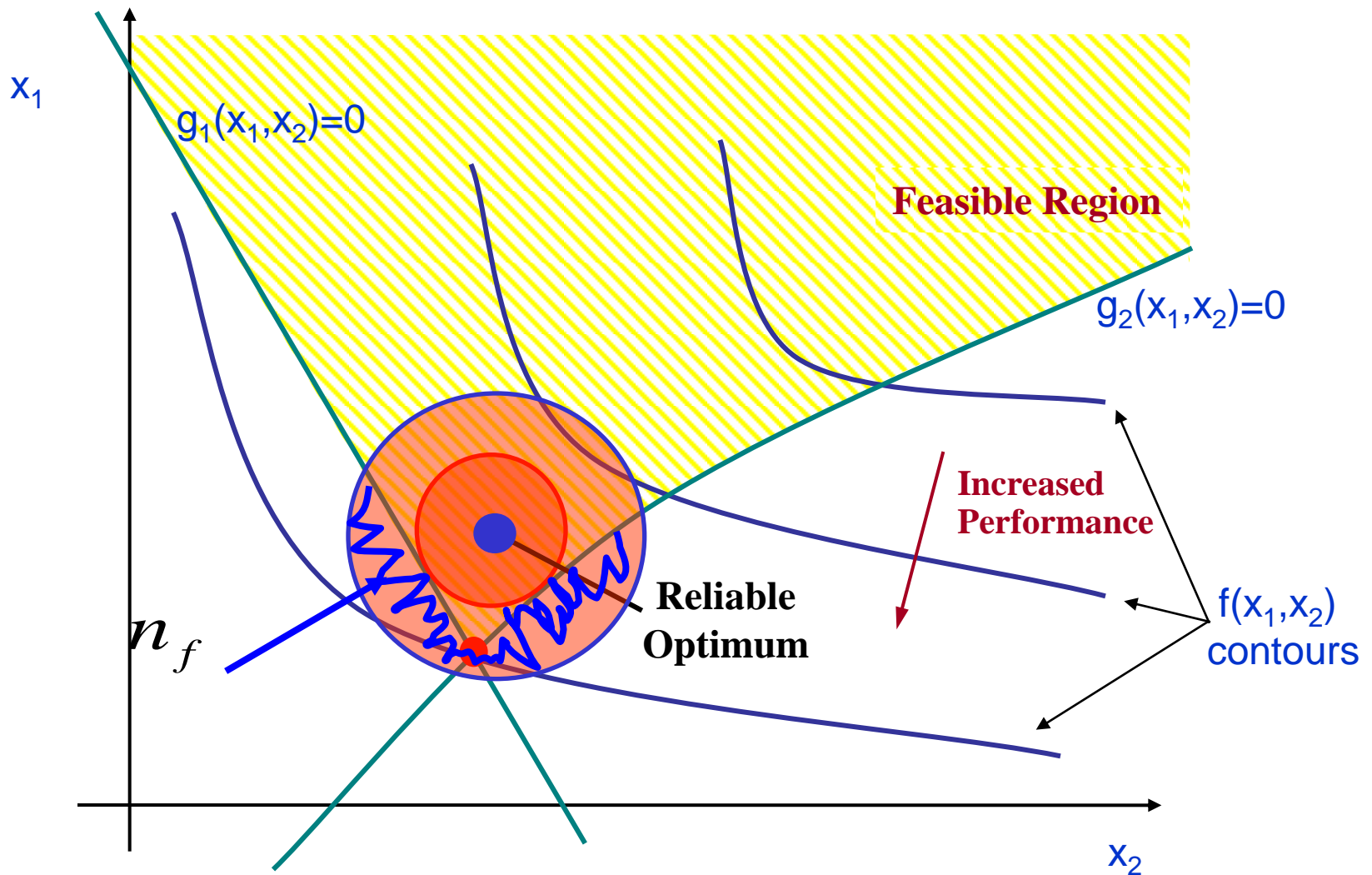
Exponential extrapolation

$$\hat{\lambda}(t) \approx \lambda_0 e^{-bt}$$



Efficient MCS (blue) approach is close to true MCS results (red)

Principle of Importance Sampling: Random Variable Case



Instantaneous **Conditional** Probability of Failure:

$$p_f^\lambda(t_i) = \int_{\Omega} \theta(\mathbf{x}; t_i) f_{\mathbf{X}}(\mathbf{x}; t_i) d\mathbf{x}$$

$\mathbf{x} = \{x_1, x_2, \dots, x_i\}$ where x_i is a realization of R.V. $X_i = X(t_i)$

$$p_f^\lambda(t_i) = \int_{\Omega} \theta(\mathbf{x}; t_i) \frac{f_{\mathbf{X}}(\mathbf{x}; t_i)}{f_{\mathbf{X}^s}(\mathbf{x}; t_i)} f_{\mathbf{X}^s}(\mathbf{x}; t_i) d\mathbf{x}$$

Sampling Joint PDF

$$p_f^\lambda(t_i) = \frac{\sum_{n=1}^{N_s(t_{i-1})} \theta(\mathbf{x}; t_i) \omega(\mathbf{x}, t_i)}{N_s(t_{i-1})} = \frac{\sum_{n=1}^{N_f(t_i)} \omega(\mathbf{x}, t_i)}{N_s(t_{i-1})}$$

$$p_f^\lambda(t_i) = \frac{\sum_{n=1}^{N_s(t_{i-1})} \theta(\mathbf{x}; t_i) \omega(\mathbf{x}, t_i)}{N_s(t_{i-1})} = \frac{\sum_{n=1}^{N_f(t_i)} \omega(\mathbf{x}, t_i)}{N_s(t_{i-1})}$$

$$\lambda(t_i) = \lim_{\Delta t \rightarrow 0} \frac{p_f^\lambda(t_i)}{\Delta t} = \lim_{\Delta t \rightarrow 0} \frac{\sum_{n=1}^{N_f(t_i)} \omega(\mathbf{x}, t_i)}{\Delta t \cdot N_s(t_{i-1})}$$

$$\omega(\mathbf{x}, t_i) = \frac{f_{\mathbf{X}}(\mathbf{x}; t_i)}{f_{\mathbf{X}^s}(\mathbf{x}; t_i)} \quad : \text{Likelihood ratio at } t_i$$

$N_s(t_{i-1})$: Safe sample points at t_{i-1}

$N_f(t_i)$: Number of failures in $\Delta t = t_i - t_{i-1}$

Likelihood ratio:

$$\omega(\mathbf{x}; t_i) = \frac{f_{\mathbf{X}}(\mathbf{x}; t_i)}{f_{\mathbf{X}}^S(\mathbf{x}; t_i)} = \frac{f_{\mathbf{X}}(x_i, x_{i-1}, \dots, x_{i-d})}{f_{\mathbf{X}}^s(x_i, x_{i-1}, \dots, x_{i-d})}$$

Decorrelation length : Maximum number of lags over which realizations of x_i are significantly correlated

$$x_i - \mu = \phi_1(x_{i-1} - \mu) + \phi_2(x_{i-2} - \mu) + \dots + \phi_p(x_{i-p} - \mu) + \varepsilon_i(N(0, \sigma_s^2))$$

To generate sampling PDF

$$f_{\mathbf{X}}(\mathbf{x}) = \frac{1}{(2\pi)^{k/2} |\Sigma|^{1/2}} \exp\left(-\frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^T \Sigma^{-1}(\mathbf{x} - \boldsymbol{\mu})\right)$$

From Yule-Walker Eqs

Estimation of Safe Sample Functions

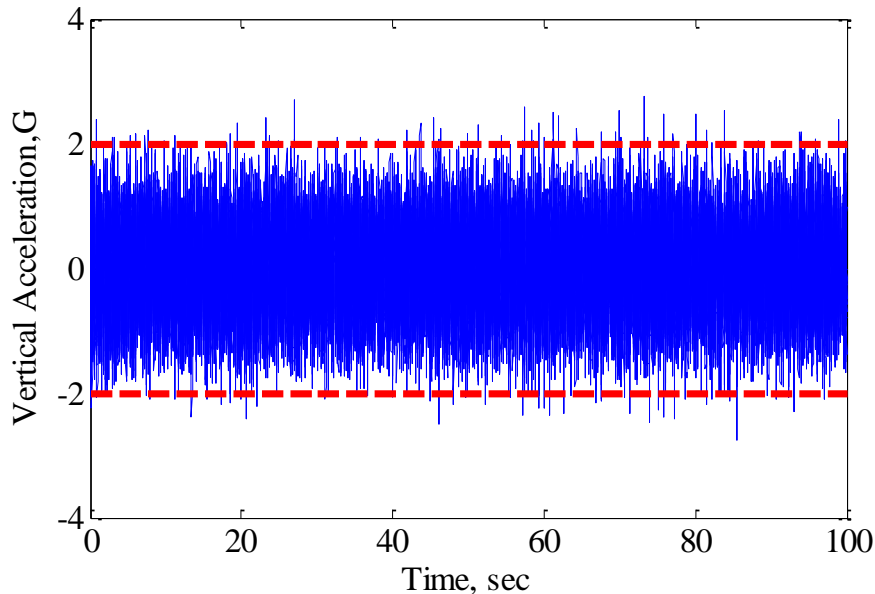
$$\lambda(t_i) = \lim_{\Delta t \rightarrow 0} \frac{\sum_{n=1}^{N_f(t_i)} \omega(\mathbf{x}, t_i)}{\Delta t \cdot N_S(t_{i-1})}$$

$$\frac{\sigma_e}{\sigma_S} x_f > S_{threshold}$$

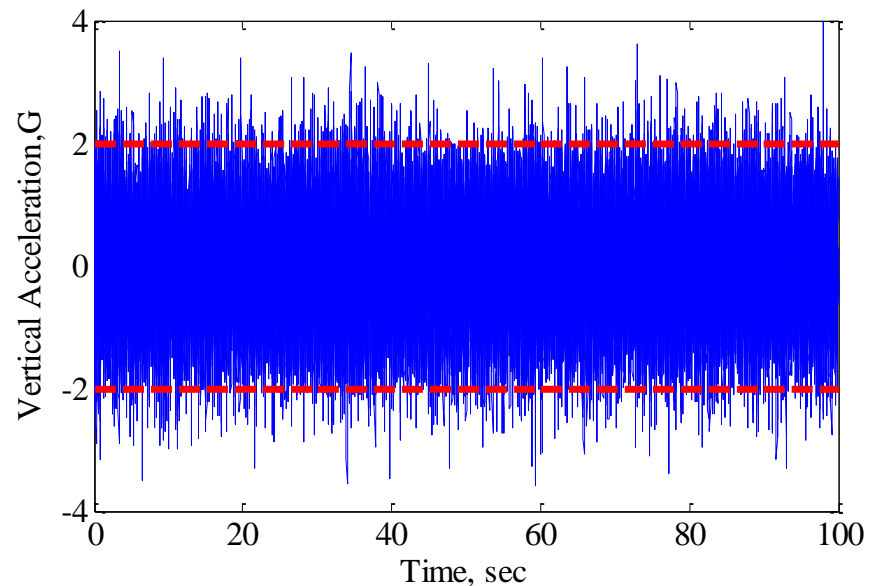
“Inflated” response

$$u_i = 1.2456u_{i-1} - 0.2976u_{i-2} - 0.1954u_{i-3} + \varepsilon_i(0, 0.5132^2)$$

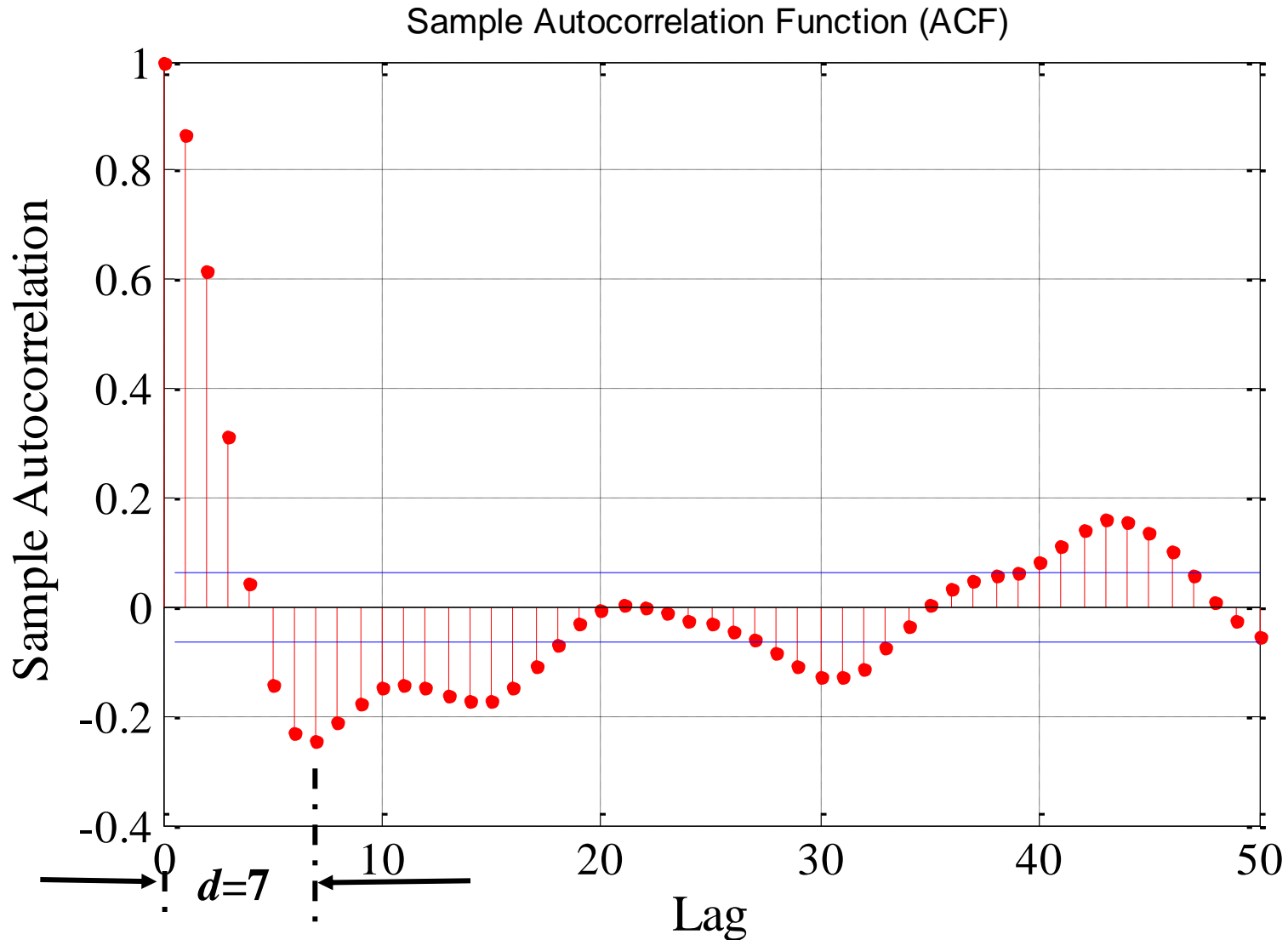
Original PDF $\sigma_e = 0.51$



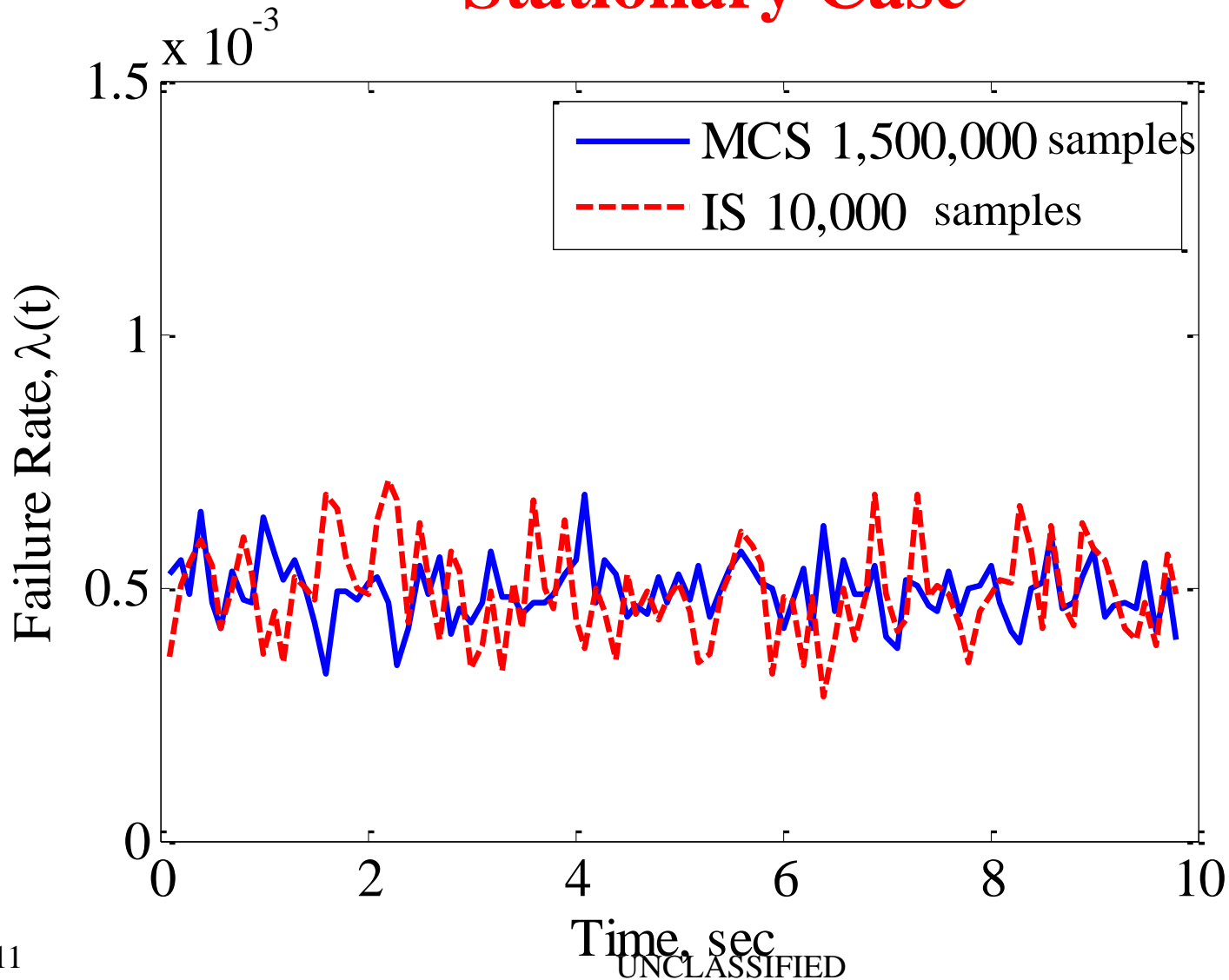
Sampling PDF $\sigma_s = 0.7$



The sampling PDF results in more failures

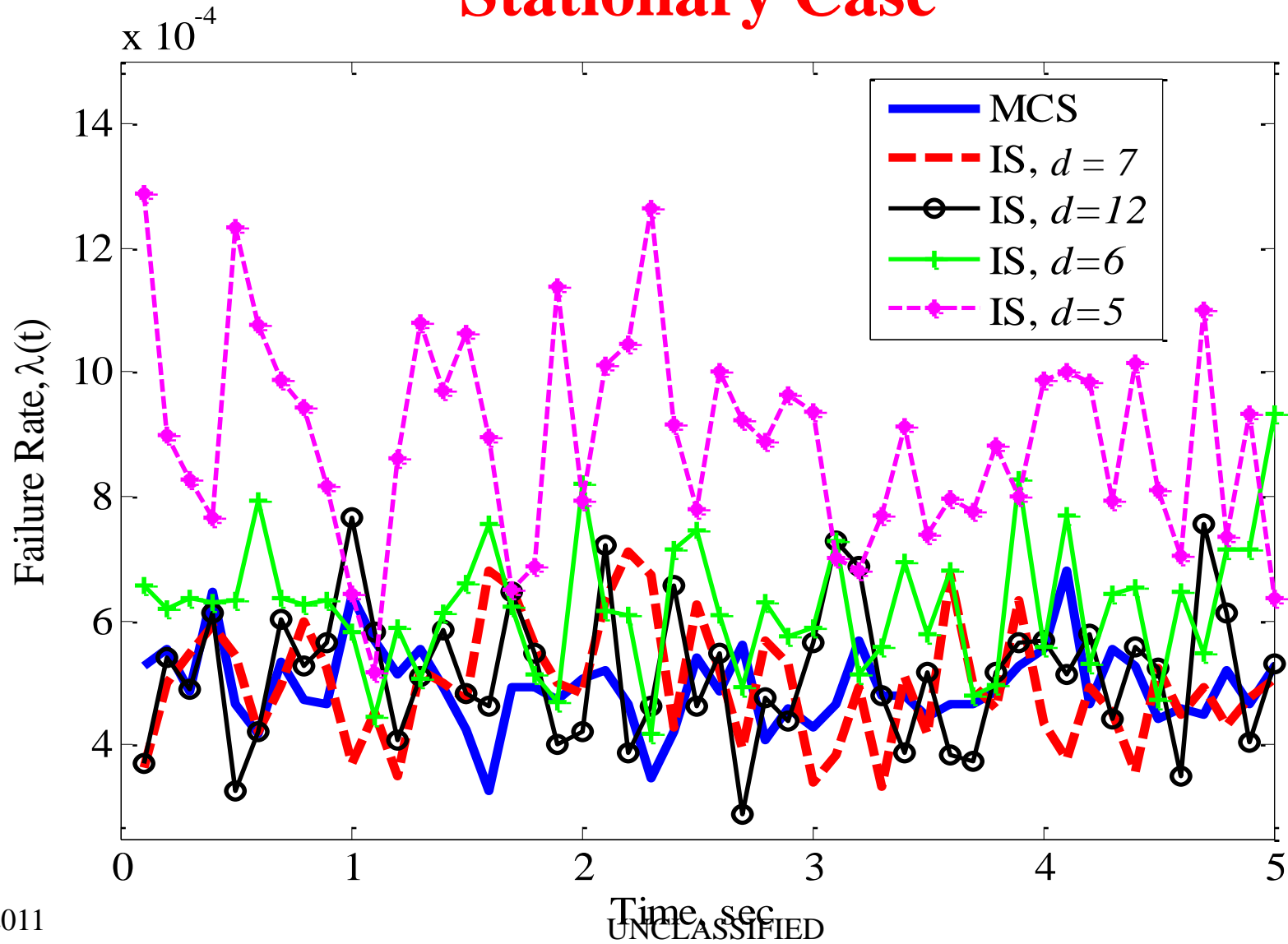


Stationary Case



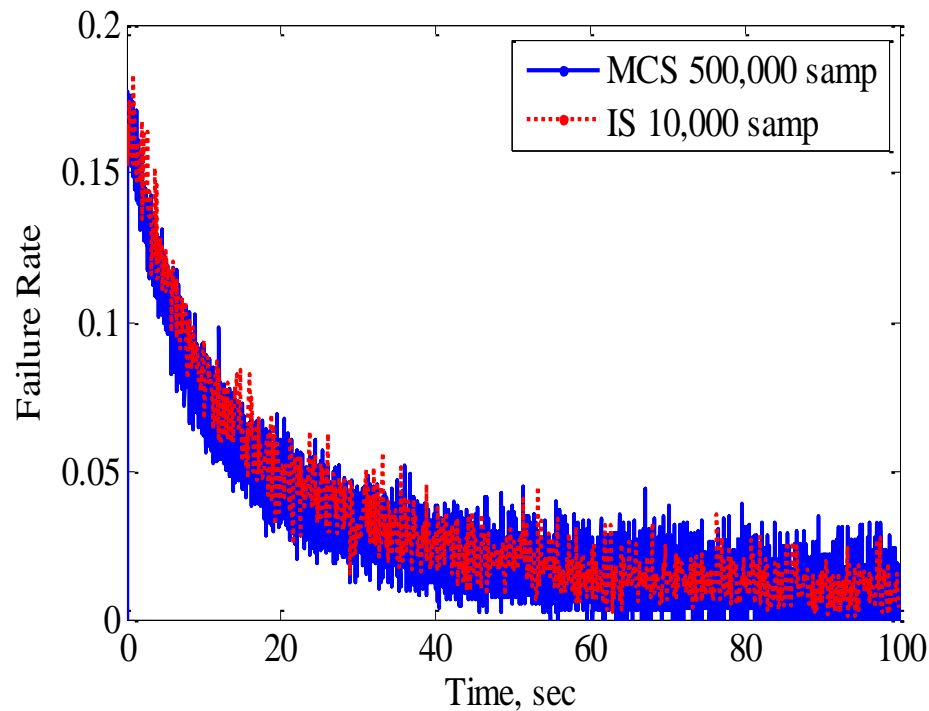
Quarter-Car Example

Stationary Case

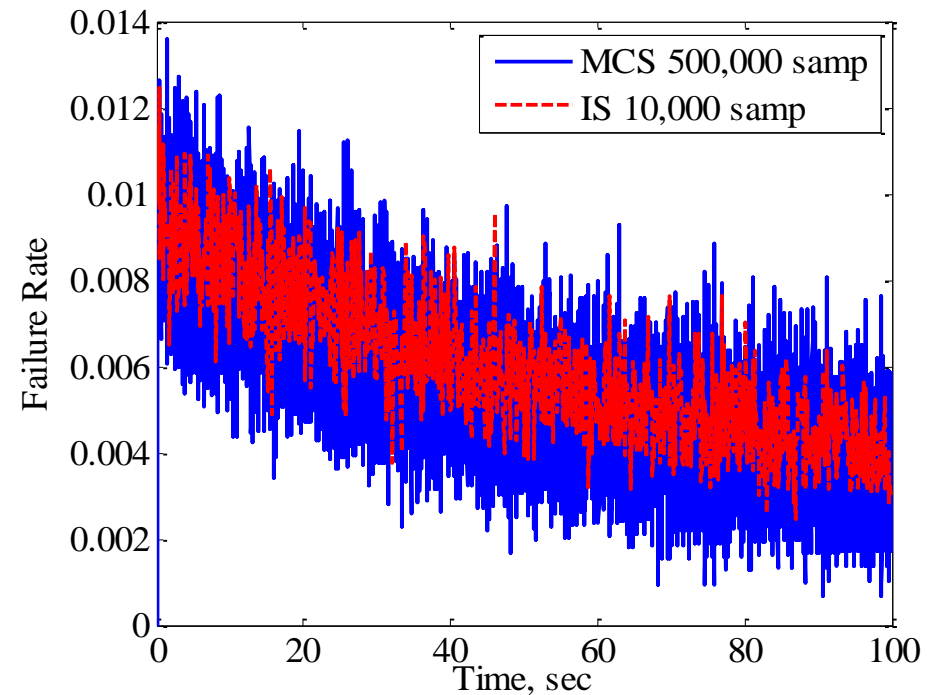


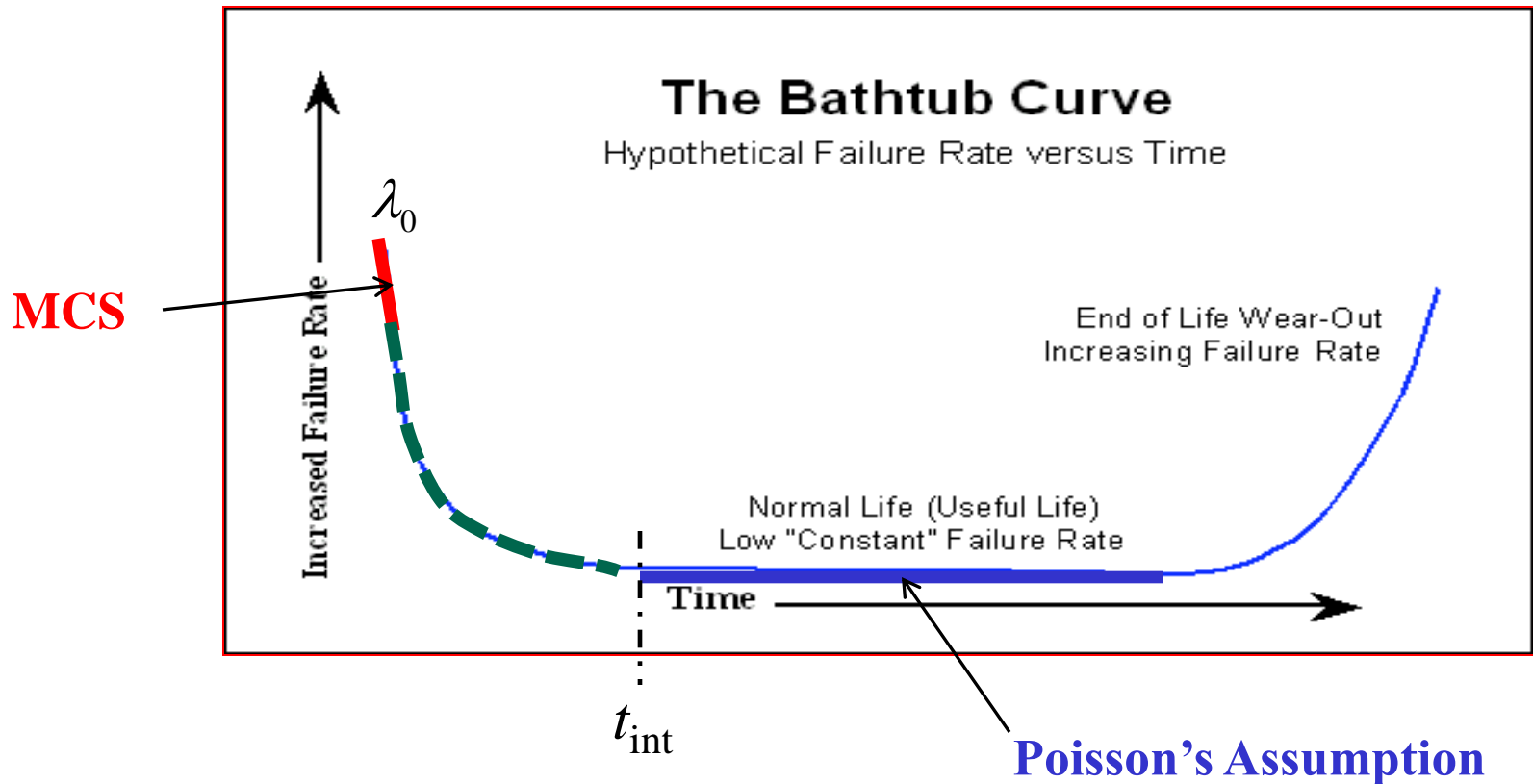
Non-Stationary Case

Threshold = 2 g



Threshold = 2.65 g





➤ Analytical methods can be used under the Poisson's assumption

➤ IS at initial time may need a few thousand output sample functions



Ongoing Work Plan



- Improve the current accelerated testing method based on importance sampling so that **only 5-10 tests are needed** (Q3)
 - ✓ Characterize the “inflated” output random process in importance sampling using “generalized” **Kriging and MLE** and/or time series

- Demonstrate the accelerated testing methodology using the **N-post (or 4-post) Reconfigurable Road Simulator** of the Physical Simulation Laboratory at TARDEC (Q3 and Q4)



TARDEC N-post Reconfigurable Road Simulator



5/24/2011

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Thanks for your attention !

Q & A

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